



Triakis Corporation

Hardware Design Document

For the

Shuttle Remote Manipulator System

**A NASA CI03
SARP Initiative 583
IVV-70 Project**



Table of Contents

1	Introduction.....	3
1.1	System purpose.....	3
1.2	System scope.....	3
1.3	Definitions, acronyms, and abbreviations.....	3
1.4	References.....	4
1.5	SRMS overview.....	4
2	General system description.....	4
3	System performance characteristics.....	6
3.1	System context.....	6
3.2	Major system components.....	7
3.3	Major system capabilities.....	7
3.4	System hardware design.....	8
3.5	RMS Computer subsystem.....	9
3.5.1	Power Converter.....	10
3.5.2	Reset logic.....	10
3.5.3	SPI Receiver.....	10
3.5.4	AFDX Interface chip.....	10
3.5.5	Video Converter ASICs.....	12

Table of Figures

Figure 1:	Simulated RMA Within Shuttle Orbiter.....	6
Figure 2:	Simulator RMS Control & Display Panel.....	7
Figure 3:	Shuttle RMS Block Diagram.....	8
Figure 4:	RMS Computer Block Diagram.....	9

Table of Tables

Table 1:	AFDX Interface Chip Memory Map Organization.....	11
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1 Introduction

This specification has been developed to support a research project funded by the NASA Software Assurance Research Program (SARP) during the fiscal year 2003 Center Initiatives (CI03) effort. A system-level, executable specification (ES) based simulation of the Shuttle Remote Manipulator System (SRMS) has been created from the requirements specified in the System Requirements (SARP-I583-001) and Simulator Requirements (SARP-I583-002) Specifications, and will be used as a vehicle for exploring the concepts described in section 2 of Triakis proposal number TC_G020614.

This document describes the hardware design developed to implement the SRMS as specified in the System Design Document (SARP-I583-101). A simulator will be created and used to evaluate the extent to which the Triakis concept of Executable Specifications (ES') achieves unambiguous communication of system requirements thereby reducing errors induced by interpretation of ambiguous specifications. It will also be used to evaluate the potential that substituting a detailed executable (DE) hardware simulation running actual embedded software, in place of the ES, has for reducing costs and maintaining test consistency through reuse of unmodified system level tests.

Further, new methods of gathering software metrics through use of the simulator will be sought, explored, and evaluated. The virtual system simulator developed for this project will be used to evaluate other potential benefits that its virtual system integration laboratory (VSIL) environment offers in support of general testability, independent validation & verification (IV&V), reliability, and safety.

As our project effort progresses, this specification will be updated to reflect changes to the scope and fidelity of system requirements due to an improved understanding of the extent that our virtual SRMS must be developed to support our research goals.

1.1 System purpose

The system specified herein is intended to represent the SRMS in a general sense only. The hardware design laid out in this document will support the development of the software, the RMS Computer DE, and many of the ancillary parts that help comprise the virtual system simulator that will be used as a vehicle to facilitate the research goals stated in Triakis proposal number TC_G020614. As such, system components and functions of the real-world SRMS that are not required to support our research goals have been omitted.

While the purpose of the actual SRMS is to facilitate the deployment and retrieval of shuttle payloads as well as extra-vehicular activity missions, the derivative SRMS will not incorporate functioning end-effectors required for these purposes. The specified SRMS will demonstrate limited control and movement capability of the RMA along with simulated cameras and video monitors showing the RMA position.

1.2 System scope

The SRMS approximately models a subset of the system characteristics of the existing NASA space shuttle RMS. Adaptations to the functionality of the actual SRMS have been incorporated to the extent required for the stated research purposes and demonstration of the research results.

1.3 Definitions, acronyms, and abbreviations

AFDX	Avionics Full Duplex Switched Ethernet
CCTV	Closed-Circuit Television
CI03	Center Initiative for fiscal year 2003
C/W	Caution/Warning



DE	Detailed Executable
ES	Executable Specification
EVA	Extra Vehicular Activity
IV&V	Independent Verification and Validation
N/A	Not Applicable
NASA	National Aeronautics & Space Administration
OSMA	Office of Safety and Mission Assurance
PDRS	Payload Deployment and Retrieval System
RHC	Rotational Hand Controller
RMA	Remote Manipulator Arm
RMS	Remote Manipulator System
RMSC	RMS Computer
RMSCP	RMS Control Panel
SARP	Software Assurance Research Program
SimRS	Simulator Requirements Specification
SRMS	Shuttle Remote Manipulator System
SyDD	System Design Document
SyRS	System Requirements Specification
THC	Translational Hand Controller
VSIL	Virtual System Integration Laboratory

1.4 References

<http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-deploy> NASA PDRS web page
SARP-I583-001 System Requirements Specification for the Shuttle Remote Manipulator System
SARP-I583-002 Simulator Requirements Specification for the Shuttle Remote Manipulator System
SARP-I583-101 System Design Document for the Shuttle Remote Manipulator System
TC_G020614 Triakis proposal to NASA for the SARP (Solicitation No: NRA SARP 0201), 14 June 2002

1.5 SRMS overview

Please refer to the NASA [PDRS](#) web page for a more complete description of the real space shuttle SRMS that this system is designed to resemble. The following excerpt is included for quick reference:

The [payload deployment and retrieval system](#) (PDRS) includes the electromechanical arm that maneuvers a payload from the payload bay of the space shuttle orbiter to its deployment position and then releases it. It can also grapple a free-flying payload, maneuver it to the payload bay of the orbiter and berth it in the orbiter. This arm is referred to as the remote manipulator system (RMS).

The shuttle [RMS](#) is installed in the payload bay of the orbiter for those missions requiring it. Some payloads carried aboard the orbiter for deployment do not require the [RMS](#).

The [RMS](#) is capable of deploying or retrieving payloads weighing up to 65,000 pounds. The [RMS](#) can also be used to retrieve, repair and deploy satellites; to provide a mobile extension ladder for extravehicular activity crew members for work stations or foot restraints; and to be used as an inspection aid to allow the flight crew members to view the orbiter's or payload's surfaces through a television camera on the [RMS](#).

2 General system description

The system designer used the following excerpt from the [NASA PDRS web page](#) as a reference source and it is given here to provide a general [SRMS](#) description for informational purposes only.

The basic [RMS](#) configuration consists of a manipulator arm; an [RMS](#) display and control panel, including rotational and translational hand controllers at the orbiter aft flight deck flight crew station; and a manipulator



controller interface unit that interfaces with the orbiter computer. Normally, only one [RMS](#) is installed during a shuttle mission, on the left longeron of the orbiter payload bay.

The [RMS](#) arm is 50 feet 3 inches long, 15 inches in diameter, and has six degrees of freedom. The six joints of the [RMS](#) correspond roughly to the joints of the human arm with shoulder yaw and pitch joints; an elbow pitch joint; and wrist pitch, yaw and roll joints. The end effector is the unit at the end of the wrist that actually grabs, or grapples, the payload.

The [RMS](#) can only be operated in a zero gravity environment, since the arm dc motors are unable to move the arm's weight under the influence of Earth's gravity. Each of the six joints has an extensive range of motion, allowing the arm to reach across the payload bay, over the crew compartment or to areas on the undersurface of the orbiter. Arm joint travel limits are annunciated to the flight crew arm operator before the actual mechanical hard stop for a joint is reached.

One flight-crew member operates the [RMS](#) from the aft flight deck control station, and a second flight-crew member usually assists with television camera operations. This allows the [RMS](#) operator to view [RMS](#) operations through the aft flight deck payload and overhead windows and through the closed-circuit television monitors at the aft flight deck station.

The orbiter's [CCTV](#) aids the flight crew in monitoring [PDRS](#) operations. The arm has provisions on the wrist joint for a [CCTV](#) camera that can be zoomed, a viewing light on the wrist joint and a [CCTV](#) with pan and tilt capability on the elbow of the arm. In addition, four [CCTV](#) cameras in the payload bay can be panned, tilted and zoomed. Keel cameras may be provided, depending on the mission payload. The two [CCTV](#) monitors at the aft flight deck station can each display any two of the [CCTV](#) camera views simultaneously with split screen capability. This shows two views on the same monitor, which allows crew members to work with four different views at once. Crewmembers can also view payload operations through the aft flight station overhead and aft (payload) viewing windows.

The arm has a number of operating modes. Some of these modes are computer-assisted, moving the joints simultaneously as required to put the end point (the point of resolution, such as the tip of the end effector) in the desired location. Other modes move one joint at a time; e.g., single mode uses software assistance and direct and backup hard-wired command paths that bypass the computers.

Four [RMS](#) manually augmented modes are used to grapple a payload and maneuver it into or out of the orbiter payload retention fittings. The four manually augmented modes require the [RMS](#) operator to use the [RMS](#) translational hand controller (THC) and rotational hand controller (RHC) with the computer to augment operations.

The [THC](#) and [RHC](#) located at the aft flight deck station are used exclusively for [RMS](#) operations. The [THC](#) is located between the two aft viewing windows. The [RHC](#) is located on the left side of the aft flight station below the [CCTV](#) monitors. The [THC](#) and [RHC](#) have only one output channel per axis. Both [RMS](#) hand controllers are proportional, which means that the command supplied is linearly proportional to the deflection of the controller.

There are two types of automatic modes that can be used to position the [RMS](#) arm: operator-commanded and preprogrammed.

The operator-commanded automatic mode moves the end effector from its present position and orientation to a new one defined by the operator via the keyboard and [RMS](#) CRT display. The arm moves in a straight line to the desired position and orientation and then enters the hold mode.

The preprogrammed auto sequences operate in a manner similar to the operator-commanded sequences. Instead of the [RMS](#) operator entering the data on the computer via the keyboard and CRT display, the [RMS](#) arm is maneuvered according to a command set programmed before the flight, called sequences. Each sequence is an ordered set of points to which the arm will move. Up to 200 points may be preprogrammed into as many as 20 sequences.



The description provided is intended to give a general picture of system functionality upon which our virtual system has been modeled. The features actually implemented and the fidelity of this virtual [SRMS](#) representation have been chosen according to what is needed to support our overall research goals.

Unless otherwise indicated, subsequent references to all elements of the [SRMS](#) and surrounding systems within this document are to be construed as referring to the virtual system elements within the simulator being developed and not the actual [SRMS](#) (in use on the NASA shuttle program) on which the virtual system is based.

3 System performance characteristics

3.1 System context

The [SRMS](#) described in the [SyRS](#) is designed as a self-contained system with few connections to the virtual shuttle within which it will function. [Figure 1](#) shows a screenshot of the simulated [RMA](#) within the virtual shuttle orbiter. Neither the manipulator positioning mechanism nor a functioning end effector will be implemented in this [SRMS](#).

The [RMA](#) is attached to the portside cargo door support longeron in the shuttle orbiter cargo bay as depicted in [Figure 1](#).

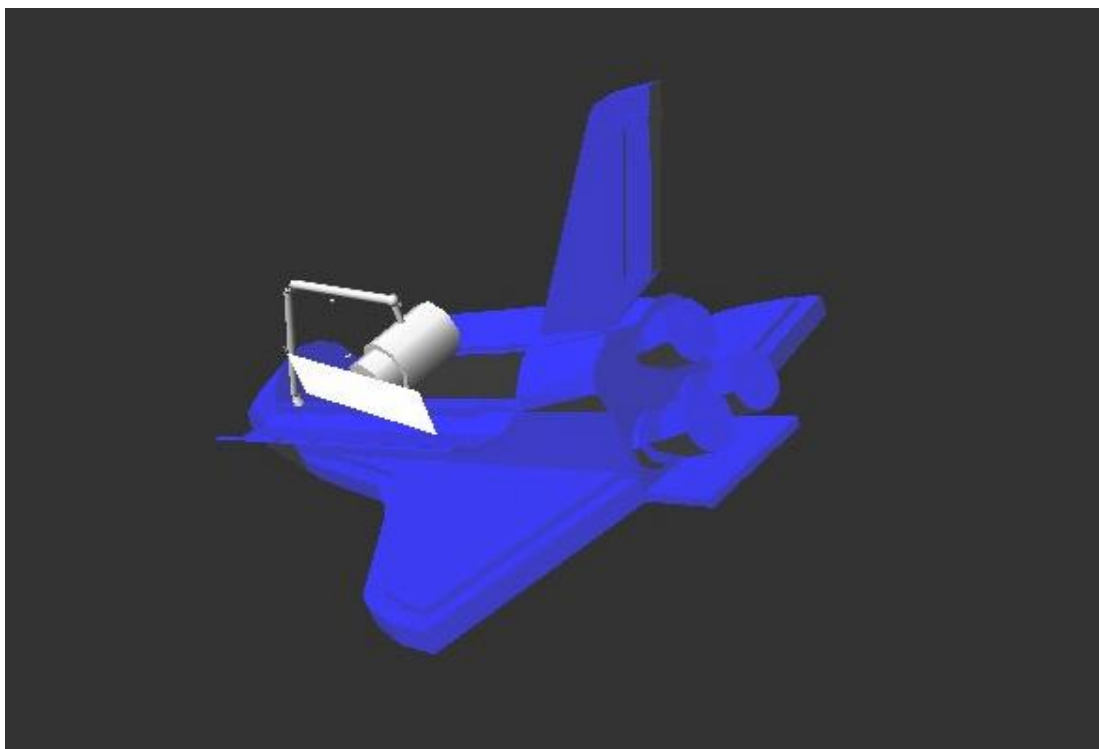


Figure 1: Simulated RMA Within Shuttle Orbiter

The SRMS draws its power from the space shuttle 28VDC and 115VAC/400Hz power supplies as required to function as described herein.

The RMS control & display panel and the closed circuit television (CCTV) monitors that the crew employs in the operation of the SRMS are provided as part of the simulator, but not located on a simulated orbiter flight deck at the



aft crew station as originally specified in the SyRS. Instead, the RMS control & display panel will be rendered in a simulator window through which the operator may operate and monitor the SRMS.

3.2 Major system components

The [SRMS](#) comprises three principal elements:

- A remote manipulator arm (RMA) ([Figure 1](#)),
- A [RMS](#) control & display panel ([Figure 2](#)), and
- A [RMS](#) control computer (RMSCC).

[CCTV](#) monitors have been simulated for visually monitoring [RMA](#) activity during operation.

The [RMSCC](#) provides the interface between the [RMS](#) control & display panel and the [RMA](#) itself.

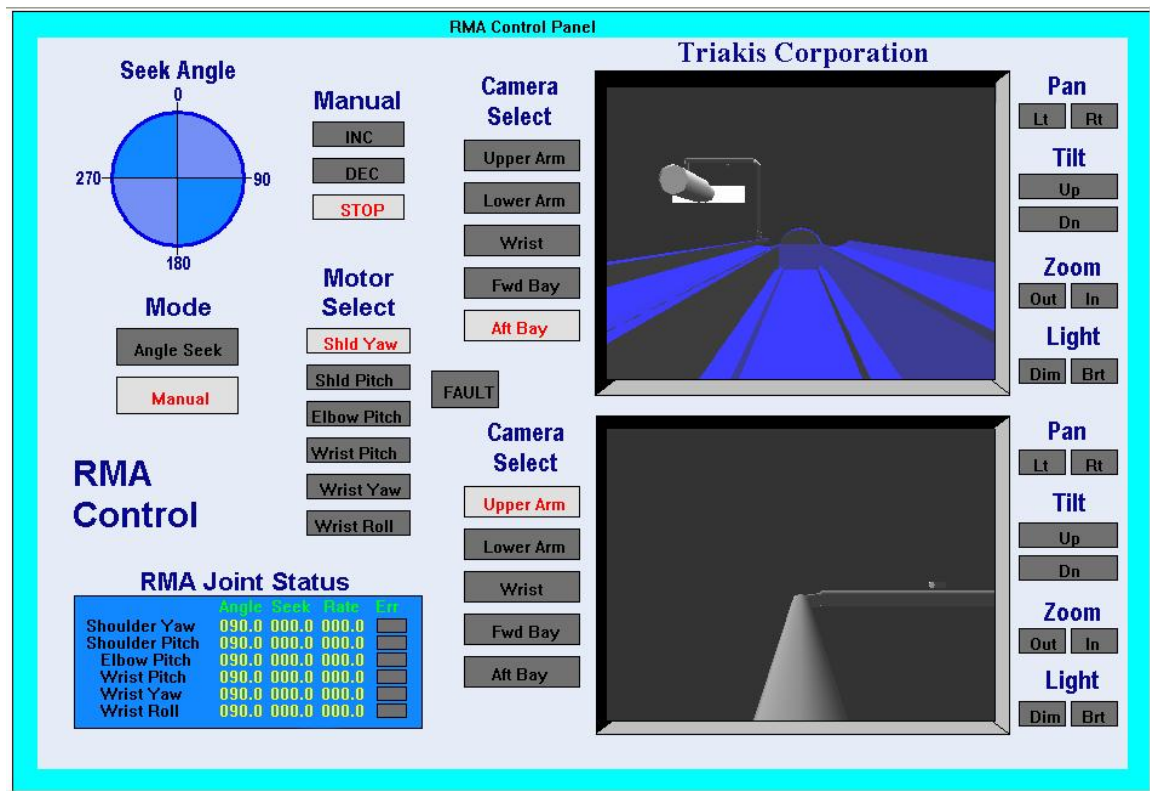


Figure 2: Simulator RMS Control & Display Panel

3.3 Major system capabilities

The RMA is implemented with 6 degrees of freedom corresponding roughly to the joints of the human arm i.e.: shoulder yaw & pitch joints; elbow pitch joint; and wrist pitch, yaw, & roll joints.

Both the upper and lower RMA booms are equipped with strain gauge sensors to measure the dynamic forces exerted on them during operation.



The SRMS design incorporates five CCTV video cameras as specified in the System Requirements Specification. Each of the cameras is equipped with pan, tilt, and zoom capability in addition to featuring a controllable light source. The cameras are located as stated in the SyRS i.e.:

- One on the RMA upper arm boom,
- One on the RMA lower arm boom,
- One at the RMA wrist joint,
- One at the aft wall of the shuttle bay, and
- One at the forward wall of the shuttle bay.

The RMS Control Panel incorporates two video display monitors and buttons as required for displaying CCTV video from any of the five video cameras.

To the left of each video monitor on the RMS Control Panel are five buttons used to select the desired camera view for display. Camera controls located to the right of the video display monitors on the RMS Control Panel are used for positioning, and zooming the camera whose view has been selected for display. While buttons have been incorporated into the control panel for controlling the lighting level of the selected camera view, the lamp parts have not been programmed to implement that functionality for this project.

3.4 System hardware design

Since no actual SRMS will be built for this project, the hardware description provided herein will be somewhat abstract. The hardware design for the RMS Computer will, however, be provided with sufficient detail required to develop a functional DE for use in our research. [Figure 3](#) contains a block diagram of the Shuttle Remote Manipulator System.

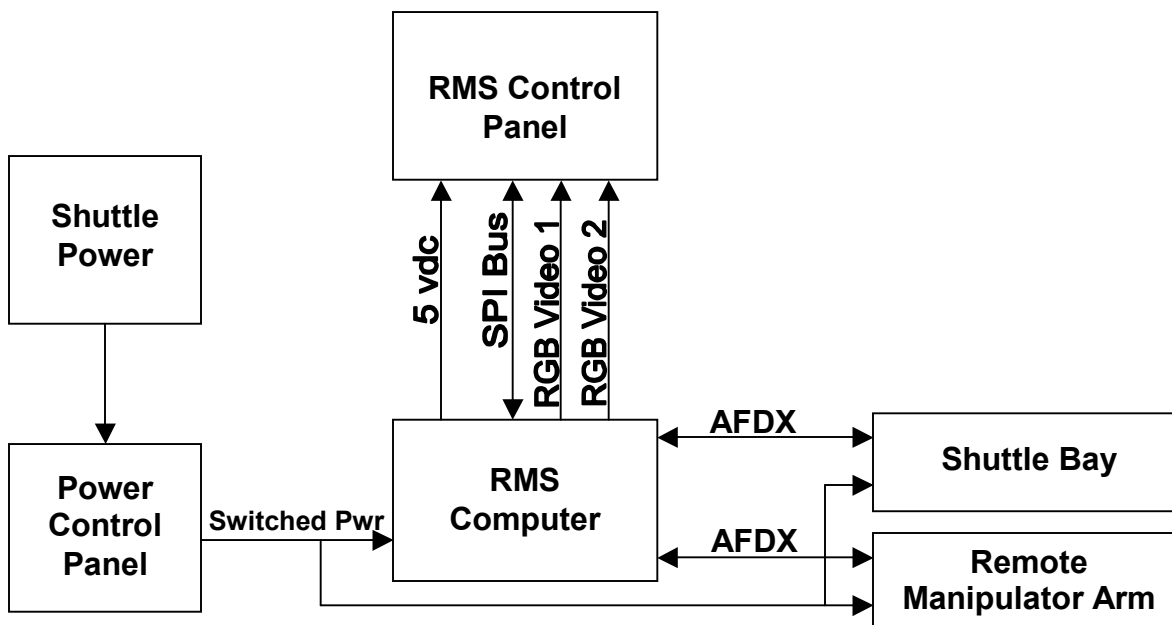


Figure 3: Shuttle RMS Block Diagram

Power is supplied to the SRMS from the 115vac main shuttle avionics power bus via a circuit breaker on the Power Control Panel. The RMS Computer converts the incoming power to DC voltages suitable to power its own



electronics as well as those within the RMS Control Panel. Switched power from the power control panel supplies power to the shuttle bay cameras and the Remote Manipulator Arm as well.

The RMS Computer communicates with the Remote Manipulator Arm and the cameras in the shuttle bay via Avionics Full Duplex Switched Ethernet (AFDX) serial high-speed databuses. In addition to commands and status information, digital compressed video from the CCTV cameras are conveyed over these databuses.

The RMS Computer converts the compressed digital camera video signals into RGB format to drive the video inputs of the two video display monitors located on the RMS Control Panel. The RMS Computer communicates with the RMS Control Panel via a Serial Peripheral Interface bus.

3.5 RMS Computer subsystem

The RMS Computer contains the central processor that is programmed to control the entire system in response to commands entered via the RMS Control Panel. A block diagram of the RMS Computer is shown in [Figure 4](#).

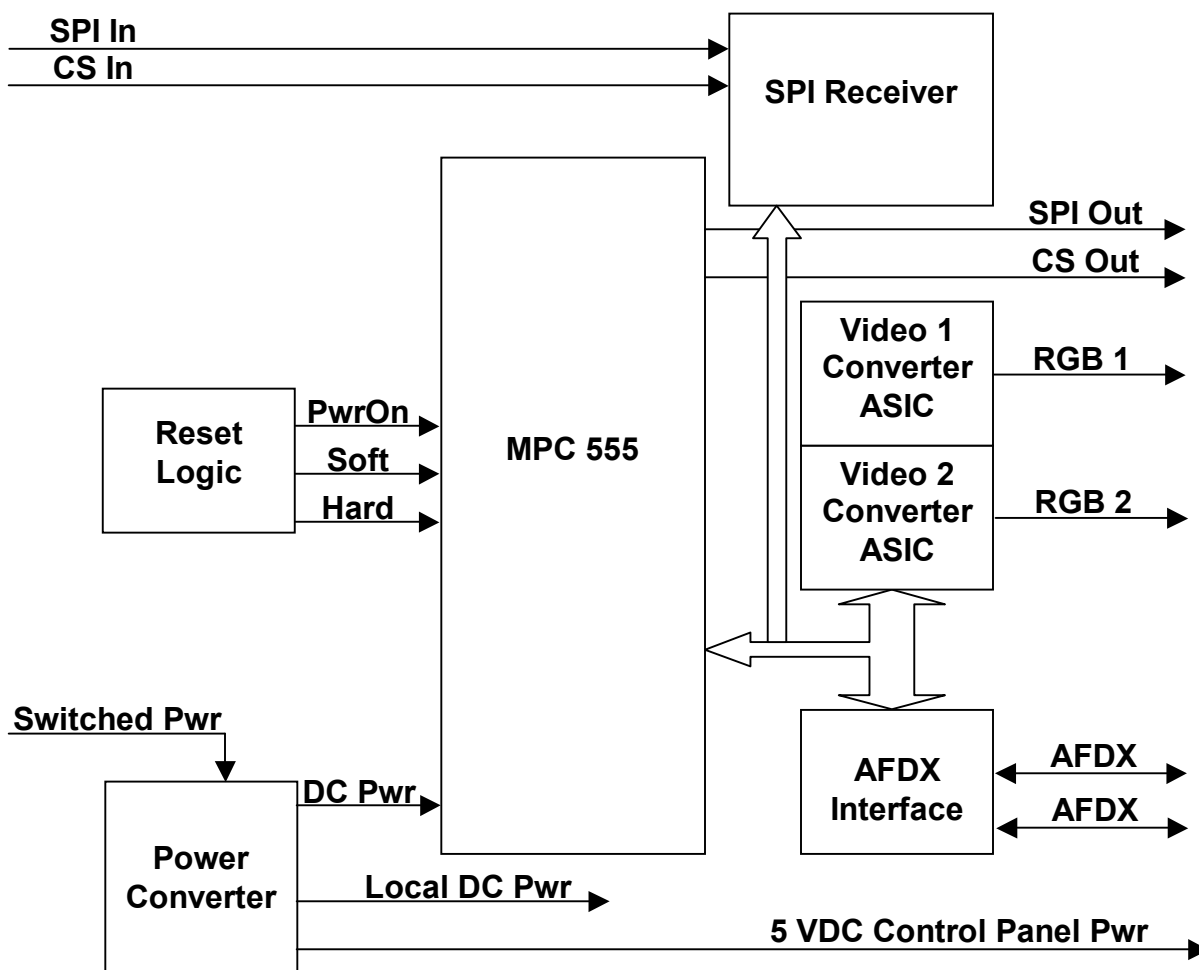


Figure 4: RMS Computer Block Diagram

The Computer design is based upon the Motorola MPC555, a PowerPC core microcontroller chip. With its high level of integrated functions, the MPC555-based design requires peripheral circuitry only for the AFDX interfaces



and to manage the conversion of digital video to RGB video. In addition to the MPC555, the RMS Computer comprises a power converter, an AFDX router, and a digital compressed video to RGB converter.

The power converter is responsible for converting the incoming shuttle electrical power into DC power required internally and by RMS Control Panel subsystem. The AFDX router directs communication between the MPC555 and all subsystem elements connected to the AFDX data buses. The Digital to RGB converter receives compressed digital camera video data from the source selected at the control panel and outputs video data in standard RGB format for display on the corresponding control panel video monitor.

Were this hardware design intended for real hardware rather than for the purposes of our project, more detail would be necessary in the following paragraphs.

3.5.1 Power Converter

The power converter is responsible for converting the incoming shuttle electrical power into DC power of the various voltages required internally by the MPC 555 and other chips on the RMS Computer board. The power converter also provides DC power to the RMS Control Panel subsystem.

3.5.2 Reset logic

The reset logic drives the Power-on, Hard, and Soft reset inputs of the MPC 555.

- a) **Power-on reset:** Asserted at power-on and remains asserted until all onboard DC voltages have reached stability at their nominal values (default delay = 20ms). Forces MPC555 to its power-up state and the software to execute a cold-start.
- b) **Hard reset:** Unused i.e. always unasserted (would typically be asserted when watchdog timer times-out to force the MPC 555 to the 'Hard Reset' state and cause the software to execute a cold-start).
- c) **Soft reset:** Unused i.e. always unasserted (would typically be asserted by external logic to cause an interrupt generally used to force the software to execute a warm-start).

3.5.3 SPI Receiver

While the MPC 555 is equipped with an SPI input channel, we chose to add a simple serial input shift register to receive SPI data from the RMS Control Panel. Interface with the MPC 555 is accomplished through memory-mapped I/O access to internal status & data registers. The memory map for the serial input device is as follows:

Memory address range	0x1000000 – 0x100000f
Data Ready status register	0x1000000 (requires a Byte-read (i.e. Getb) operation) Data Ready = 1 when data from the control panel is available. Data Ready is automatically reset to 0 after it has been read.
Received Data buffer	0x1000000 – 0x100000f All data words are 16-bits (requires a Word-read (i.e. Getw) operation)

The current implementation of the RMS Control Panel sends packet sizes of two words only (refer to the System Design Document SARP-I583-101 for details). The remaining 14 words are available for future growth.

3.5.4 AFDX Interface chip

The AFDX Interface manages communications between the MPC 555 and all SRMS devices connected to the AFDX high-speed serial data bus. The AFDX Interface chip occupies the following 4 megawords of memory-mapped address space:

AFDX Interface Address Range: 0x2000000 – 0x23fffff (AFDX base address = 0x2000000)



Table 1 shows the organization of the memory map used for managing AFDX communications. To access these locations, add the memory location offset address to the AFDX base address.

Table 1: AFDX Interface Chip Memory Map Organization

Hex Address Offset	Assignment
0000	Motor Command Memory
0fff	
1000	Motor Command Pointer
1fff	
2000	Image Buffer Data Pointer
2fff	
3000	AFDX Command Buffer
3fff	
4000	AFDX Message Type
4001	AFDX Destination Address

The **Motor Command Memory** area is used for storage of incoming data from the various motor controllers attached to the AFDX bus. This memory area is divided into consecutive 16-word data-blocks reserved for the storage of incoming data from each of the SRMS motors.

The **Motor Command Pointer** area is used for storage of pointers to the command memory data-blocks for each of the AFDX-addressed motors. The storage location for a given motor is indexed by the AFDX address for that motor. For example, the Elbow Pitch motor has an AFDX address of 0x300 so its command memory pointer is located at offset address 0x1300, which, in turn will contain the address 0x0032. Refer to the System Design Document SARP-I583-101 for the AFDX addresses of the 21 motors used in the SRMS.

In addition to the command and data pointer memory, there is a 4-megabyte data memory buffer internal to the chip for storage of incoming video data from each of the video cameras. This memory is divided into 8 half-megabyte video image buffers corresponding to the maximum number of video cameras supported by the chip. When a camera image sensor is sent a 'QueryResponse' command, (as if by magic) the video image buffer corresponding to the camera queried is filled with the current camera video image.

The **Image Buffer Data Pointer** area is used for storing pointers to the half-megabyte video image buffer for each of the cameras. The video image buffers are only accessible through the pointers stored in the Data Pointer area. The buffer pointer address for each of the five camera image sensors is determined in the following manner:

Pointer Location = AFDX base address + Data Pointer base address + Image Sensor AFDX address

For example, the pointer location for the wrist camera image sensor is $0x2000000 + 0x2000 + 0x435$, or $0x2002435$. To link this to the first video image buffer block, a 0x0 would be written to this address. To point to other image buffer blocks simply load the pointer location with the value: $512 * 1024 * n$, where 'n' is the buffer number (0-7).

The **AFDX Command Buffer** area is used for storage of the data content for the command about to be issued. Refer to the System Design Document SARP-I583-101 for the AFDX commands and formats used in the SRMS. For this project, no more than 3 AFDX command words are used so most of this buffer area remains dormant. Command words are written sequentially beginning with location 0x2003000.



The **AFDX Message Type** (Query All, Query Response, Execute Command) for the command about to be issued is written to location 4000. Refer to the System Design Document SARP-I583-101 for the AFDX command formats used in the SRMS.

Writing the address of the target device to the **AFDX Destination Address** (location 4001) automatically initiates transmission of the AFDX command.

3.5.5 Video Converter ASICs

The two video converter ASICs used in this design are used for converting the compressed video images received from the camera image sensors into RGB format to drive the RMS Control Panel video monitor inputs. The MPC 555 communicates with the two identical ASICs through the following assigned memory-mapped address spaces:

Video Converter 1 Address Range: 0x3000000 – 0x30ffff

Video Converter 2 Address Range: 0x4000000 – 0x40ffff

In order to send a video image to the RMS Control Panel, copy the entire video image from the AFDX video image buffer to the desired video converter. Upon completion of the video image buffer copy, write a 0x0 to video converter memory location offset 0x80000 (i.e. address = Video Converter base addx + 0x80000, e.g. 0x3080000). This action signals the video converter to perform the RGB conversion and send the result to the RMS Control Panel.